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Final Technical Report

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**"A Study To Examine The Feasibility Of Using Surface
Penetrators For Mineral Exploration"**

by

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A STUDY TO EXAMINE THE FEASIBILITY OF USING
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Preface

During the period covered by this grant, the feasibility of using surface penetrators in earth applications has been examined. This report summarizes penetrator applications in exploration for mineral resources only and it describes instrumentation for future penetrators. Portions of this report have been incorporated into a more extensive report examining other penetrator applications in exploration for fossil fuel, geothermal resources, and in environmental and engineering problems. The entire report, entitled "THE PENETRATOR IN EARTH APPLICATIONS - A Study To Determine The Feasibility Of Using Penetrators In Exploration For Natural Resources And Environmental And Engineering Applications" by Blanchard (JSC), Davis (SJSU), and Shate and Polkowski (LFE) will be published as a NASA technical publication.

INTRODUCTION

The N.A.S. Science Board has recommended that surface penetrators be employed to obtain scientific data on a Mars mission in the 1978 to 1983 period (Space Science Board, 1974). Penetrators can also be useful in earth applications. They can play a role in exploration for mineral, fossil fuel, and geothermal resources. In addition, they are ideally suited to monitor some environmental hazards and to measure engineering properties in remote regions.

Penetrators are missile-shaped objects (see Figure 1) which may be launched from an orbiting spacecraft, dropped from an aircraft or ship, or fired into the ground from the bed of a truck. Carrying a variety of sensors, they can reach depths up to 200 feet and perform in situ analyses. Part of the penetrator is designed to remain at the surface to provide a platform for both communications and some sensors. An umbilical is unfurled to provide electrical connections to the buried forebody which contains sensors and a power supply. Penetrators equipped with appropriate sensors can be dropped at preselected remote sites to perform in situ geochemical, geophysical, and biological analyses on samples of soil, sediment, rock, groundwater and soil gas. Transmission of data via satellite, aircraft or ground stations could begin within minutes.

The versatility of penetrators has been demonstrated by the development of very rugged microminiaturized analytical instrumentation for the Mars Penetrator Mission (Blanchard et al., 1976; Manning, 1977). In this penetrator application, sophisticated instruments are to be developed and

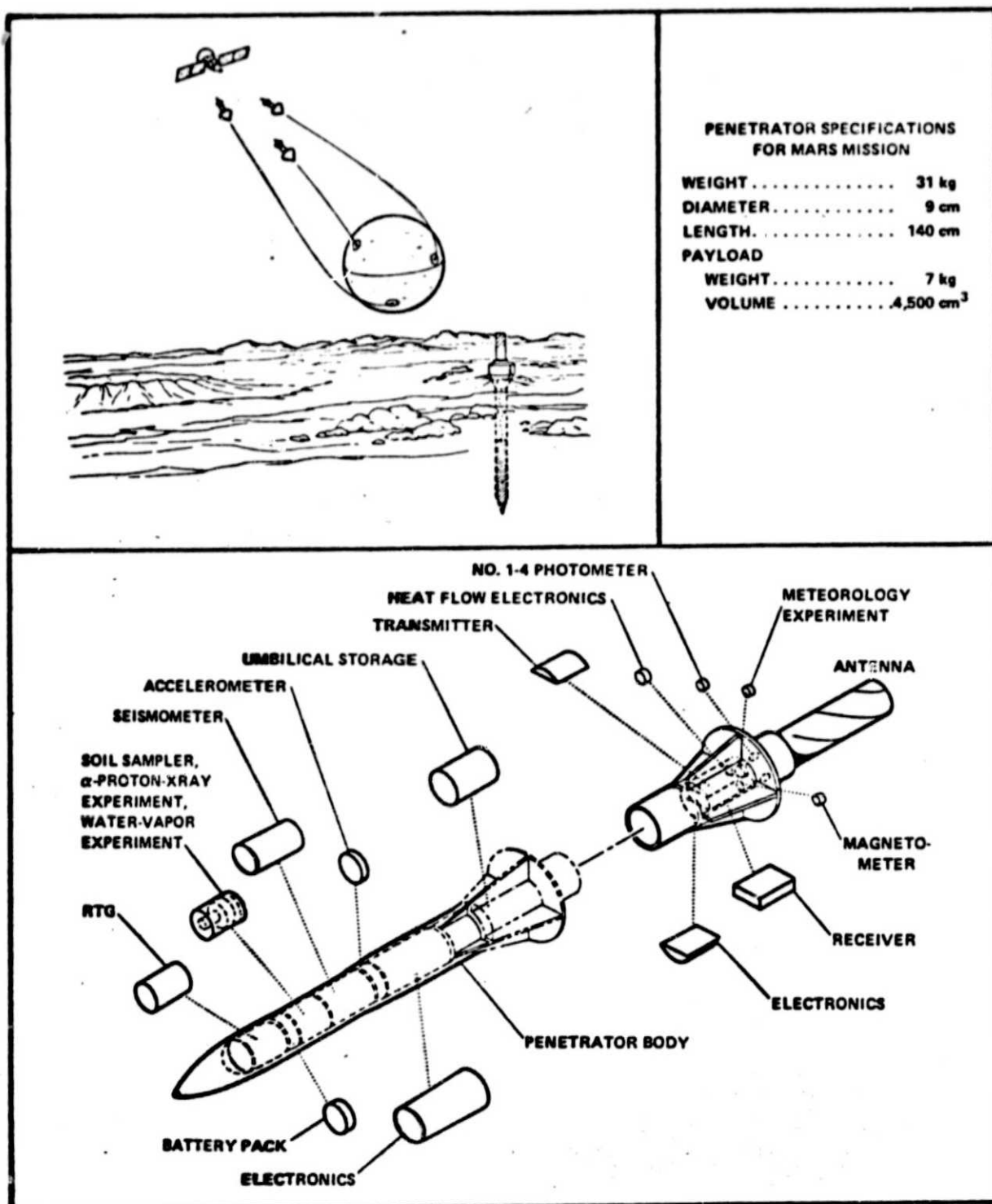


Figure 1. A possible Mars penetrator configuration. Insert in upper left corner shows penetrator deployment on Mars (Manning, 1977).

emplaced beneath a planet's surface to study seismology, magnetometry, heat flow, and geochemical properties. The penetrator also appears to provide useful applications on earth during the early reconnaissance stages of regional exploration because it can rapidly acquire data over a vast region. It could provide ground truth to remote sensing data and define favorable areas for detailed exploration. There are circumstances where the penetrator may be desirable in detailed site surveys because it can be used as an alternative to drilling in inaccessible areas. However, penetrators should be considered to supplement, not to supplant, existing exploration methods. The penetrator's advantages are even greater for implanting instruments into oceanic sediments because it would eliminate the need for some deep sea drilling and coring operations. In addition, the penetrator appears ideally suited to monitor parameters that allow early warnings to be made of impending disasters. Volcanic eruptions, earthquakes and landslides exhibit precursory anomalies before the actual event. Such parameters could be continually monitored by a network of strategically placed penetrators equipped with tiltmeters and seismic sensors. Also, the penetrator has the ability to make useful civil engineering measurements of soil, rock, snow and ice in remote regions. These measurements include subsurface profile investigations and determination of physical properties such as deducing the properties of layered structures and depth to bedrock from the deceleration record. Finally, the rugged, miniaturized instrument packages developed for penetrators can also be useful for bore hole logging.

Additional instruments will certainly be developed in the years ahead to further expand the analytical capabilities of penetrators for earth and planetary applications. These developments will further enhance the use of penetrators for resource exploration, and environmental and engineering applications.

The demand for mineral resources is ever increasing. If the present rate of usage continues many metals will be depleted in less than a century. Yet, we have entered a period in history where previously underdeveloped nations are becoming industrialized and are demanding their share of resources. If the rest of the world consumed metals at the same rate as the United States, many critically needed metals would be exhausted in less than ten years (Tien et al., 1976).

The rate of new mineral discoveries in the United States has drastically declined in the past two decades and the gap between consumption and domestic production is ever widening. The primary reason for this is that nearly all exposed and buried ore deposits with easily recognizable surface expression have been found. Future exploration must concentrate on more deeply buried and/or lower grade ore deposits in more remote regions. Consequently, exploration and development costs are increasing; costs which the consumer ultimately pays. Discovery of new ore deposits that have no easily recognizable surface expression will require more sophisticated exploration techniques. Penetrators equipped with a variety of geochemical and geophysical sensors may make in situ measurements that are necessary to identify potential ore deposits.

CHARACTERISTICS OF DEPOSITS

A concentration of minerals from which one or more materials can be profitably extracted is called an ore. A wide variety of ore deposit types exist that differ in mineral composition, host rock and mode of origin.

Some ore deposits have crystallized from a magma. Some ore deposits have sublimated from a vapor phase while others have precipitated from

an aqueous solution. The ores precipitated from aqueous solutions may range from high temperature-pressure mineral assemblages formed at great depth to low temperature-pressure assemblages formed in near surface environments. Still other ore deposits are sedimentary in origin and may have been concentrated by chemical, mechanical and biological processes. Weathering processes can also produce ore deposits from barren rock by leaching away more soluble components and accumulating residual concentrations of Fe and Al oxides or Ni bearing silicates in laterites. Weathering processes can also modify, and improve the grade, of an existing ore by a process known as supergene enrichment. In this process, descending ground water leaches soluble metals from the oxidizing zone and redeposits them as sulfides in the reducing zone.

Primary Dispersion

The ore-forming process responsible for the formation of the ore body largely determines the subsurface characteristics of the ore. The migration and redistribution of ore and associated elements in the rock or sediments contemporaneous with the formation of the ore is called primary dispersion. Primary dispersion haloes may extend, laterally and vertically, for hundreds of meters away from the ore, or they may be limited to centimeters in width. Major factors determining the size and shape of the halo are mobility characteristics of the elements; microfractures in the rock; porosity and permeability of the host rock; tendency of host rock to react with the ore fluids; and physical parameters of the fluids such as viscosity, temperature and pressure (Beus and Grigorian, 1977).

Secondary Dispersion

Redistribution of ore and associated elements occurring after ore formation produces secondary dispersion patterns. Secondary dispersion haloes are primarily produced by oxidation and weathering of the ore and typically are of much larger aerial extent than primary haloes. Oxidation of an ore in a near-surface environment may result in the formation of brightly colored iron oxide surface cappings known as gossans. Even without visual surface evidence, ore elements may become concentrated in the soil and water. Such abnormally high concentrations, or positive anomalies, may occur in surface and ground water and in stream sediments miles downstream from an ore deposit (Levinson, 1974). The actual intensity and position of the anomaly depends on the mobility of the ore elements in the surface environment and the prevailing hydromorphic conditions. For example, a more mobile element (e.g. Zn) forms a stronger anomaly than one less mobile (e.g. Pb), and hydromorphic conditions may dislocate the anomaly so that it does not correspond with the exact position of the ore below the surface (see Figure 2). The actual size, shape, and position of the secondary dispersion halo depends on many factors which include, besides element mobility and hydromorphic properties, the Eh and pH of the water and the type and stage of development of the soil (Bradshaw, 1975).

In addition to dispersion haloes created by oxidation and weathering of the ore, diffusion of elements which were present in the ore

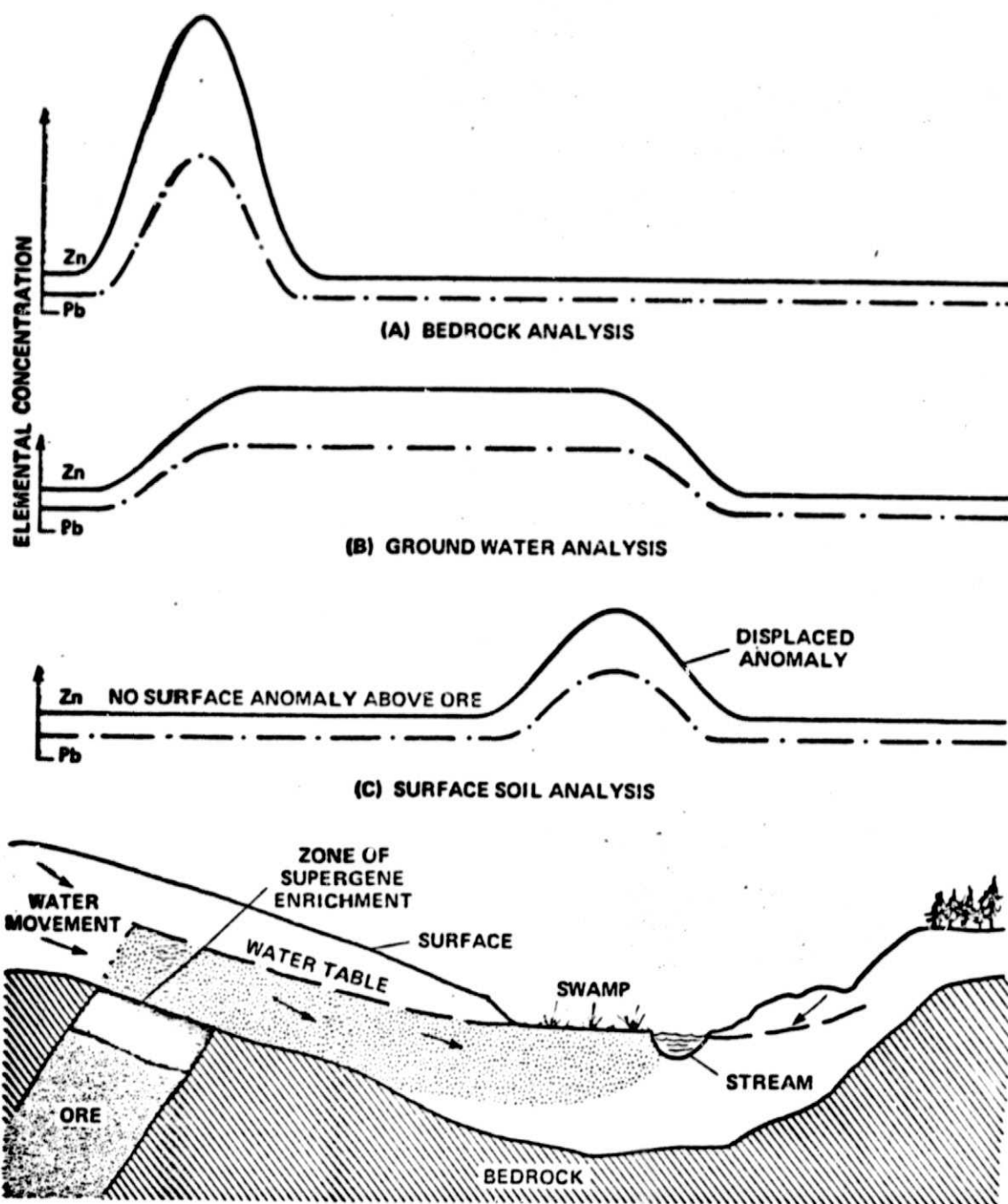


Figure 2. Idealized geochemical anomalies showing zinc and lead concentrations in (A) bedrock, (B) ground water and (C) surface soil over a hypothetical sulfide ore (modified from Joyce, 1976).

originally (e.g. Hg vapor), or elements that were formed later by radioactive decay (e.g. Rn), can also form dispersion haloes (See Figure 3).

All characteristics of an ore deposit, its primary and secondary dispersion features, and all aspects of the particular geologic environment must be considered when designing an exploration program and interpreting exploration data.

EXPLORATION PARAMETERS

In the past, exploration was largely carried out by prospectors who looked for visual expressions of mineralization. Modern exploration methods concentrate on identifying more subtle, chemical and physical characteristics of ore bodies and their associated dispersion haloes.

The most direct method relies on searching for positive chemical anomalies of ore elements in soil, in sediments and rock, in soil gas, or in surface and groundwater. In place of ore elements, one can also search for positive anomalies of so-called pathfinder elements which may be more mobile in the particular environment, or they may be easier to analyze. These pathfinder elements may be more volatile, non-ore elements that were minor constituents of the original ore bearing fluids (e.g. Hg, Ba, F, etc.), or they may be oxidation or decay products of the ore (e.g. SO_2 , H_2S , He, etc.) (Boyle, 1974).

Another, less direct, method for locating ore deposits relies on measuring diagnostic physical properties. Higher specific gravity

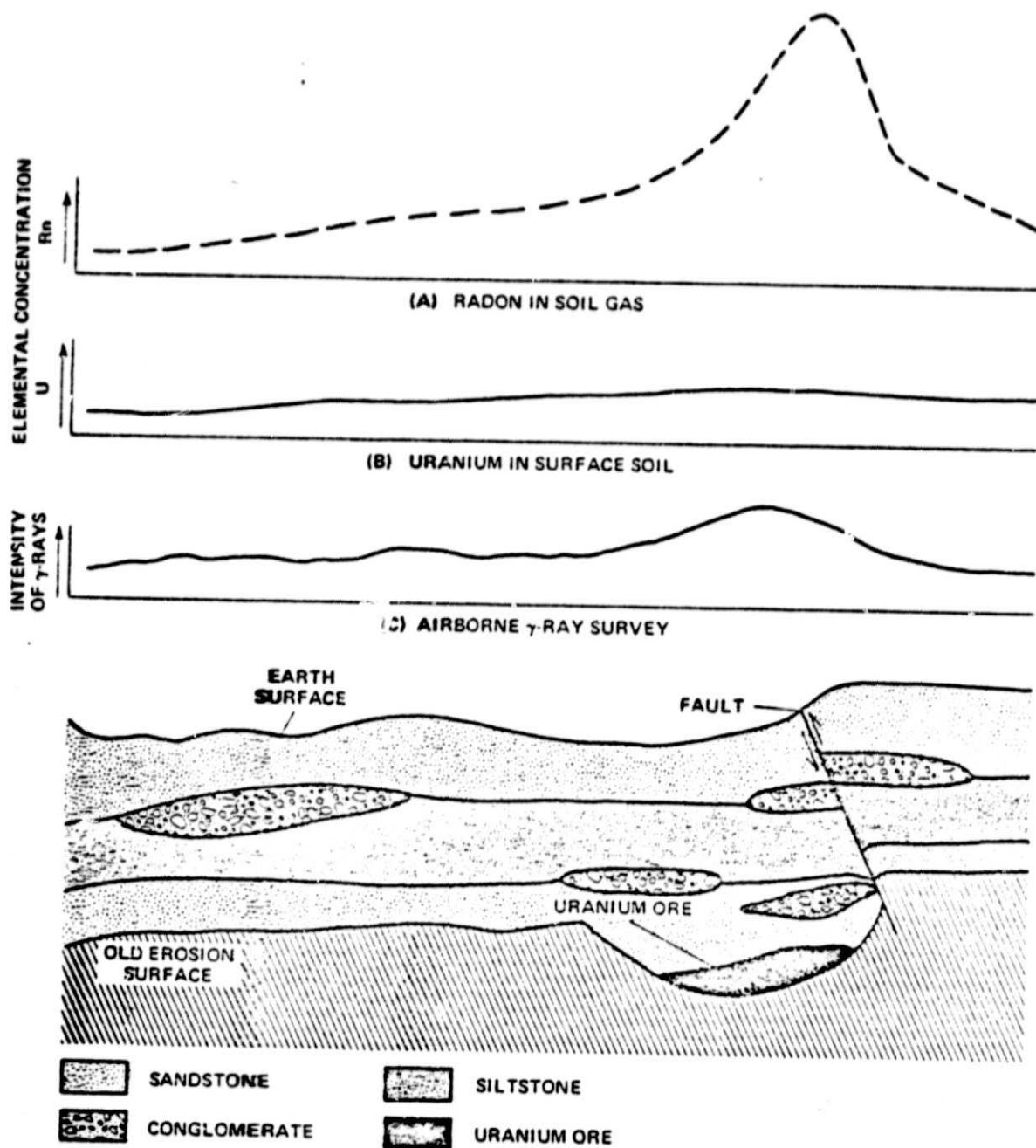


Figure 3. Schematic cross section of uranium ore in ancient stream channel and idealized profiles of (A) radon in soil gas, (B) uranium concentration in soil and (C) gamma ray intensity above the ore (based on data in Stevens *et al.*, 1971).

than the surrounding rock, radioactivity, and the presence of magnetic minerals, either as ore or as an accessory mineral, may be indicative of some ores. Diagnostic electrical properties can be measured by either utilizing natural telluric currents or by artificially inducing currents into the earth. Some of these geophysical methods are presently employed in remote sensing, but may be hampered by their inability to analyze more than a shallow surface layer.

Penetrators equipped with the appropriate sensors could provide the third dimension to remote sensing with analyses at depth.

Types of Samples Used in Exploration

The physical and chemical properties chosen as ore indicators in an exploration program largely determine the method of analysis to be used, however the type of sample (e.g. sediments, water, soil, soil gas, rock) is also a determining factor.

Analysis of the fine fraction of stream sediments is one of the most widely used techniques in exploration surveys because it provides a composite of materials present in the drainage area. In areas of internal drainage, lake sediments may function in the same manner, as may aeolian sediments in areas of long-term prevailing winds. Surface and groundwater similarly reflect the chemical composition of a larger area, but concentrations of ore elements are generally very low, requiring very sensitive methods of analysis, and surface waters show large seasonal variations. Soil analysis has been very successfully used in residual soil, but in transported and immature

soil dispersion of ore elements may be very limited or erratic. Soil gas analysis constitutes a recent development in geochemical prospecting but it may provide a method for detecting deeply-buried deposits in surface environments. Rock samples have not been widely used in reconnaissance surveys. However, with increasing demand for disseminated, low-grade ore deposits and with attempts to establish geochemical provinces related to ore genesis, rock sample analysis may become more important (Andrews-Jones, 1968; Levinson, 1974).

Penetration Depth

The exploration parameters previously discussed, such as physical and chemical properties to be measured, types of sample, and method of analysis, must be carefully considered in any exploration program. However, if penetrators are to be employed, an additional parameter must be considered, namely that of penetration depth.

The penetration depth depends on the nature of the ore deposit, the soil development and whether the soil is residual or transported overburden. For example, a low-grade, disseminated ore deposit may be economically exploited only in open pits with a minimum of overburden. On the other hand, a scarce, high-grade ore may be profitably mined at great depth. When exploring for nickel or aluminum in laterites, sampling depth should be limited to the leached soil horizon and weathered bedrock, since the ore is the residuum of chemical weathering. For most other ore deposits with residual soil development the soil zone of accumulation or weathered bedrock would be the target

depth. The actual depth to weathered bedrock varies greatly from one area to another, since soil development depends on climate and topography. Often the overburden is not residual soil but transported materials such as alluvium, glacial deposits or landslides. In these cases, it may be desirable to penetrate the transported overburden to analyze the weathered bedrock. Alternatively, in regional reconnaissance surveys it may be preferable to analyze the transported material to determine if mineralization exists in the drainage area that would warrant further exploration.

THE PENETRATOR'S ROLE IN EXPLORATION

The penetrator is potentially capable of playing a role in exploration for all kinds of mineral deposits. Equipped with the appropriate geochemical and geophysical sensors it can detect primary and secondary anomalies or physical properties that are indicative of an ore deposit. Specific examples of ore deposits, their geologic environment and pertinent exploration parameters, for which the penetrator may be potentially useful are listed in Tables 1A and 1B. These tables are not meant to be all inclusive. The examples were selected on the basis of being scarce metal resources or deposits that appear particularly amenable to exploration with penetrators (e.g. laterites).

The stage of exploration at which penetrators would generally be most useful is in the early stage of regional reconnaissance. Detailed exploration requires high density sampling and penetrators would be practical only under conditions where they can provide an alternative to drilling or in extremely inaccessible regions. In addition, there may be special environments, particularly in the oceans, where specifically modified

TABLE 1A. ORE DEPOSITS AND EXPLORATION PARAMETERS FOR WHICH PENETRATORS MAY BE POTENTIALLY USEFUL

Ore Deposit	Occurrence and Geol. Setting	Type of Sample	Direct Ore Indicator ^a	Indirect Ore Indicators ^{a*}	Sampling Depth	Method of Analysis
Uranium in sedimentary rock	Mostly epigenetic impregnations in fluvial sandstone or conglomerate. Also low-grade, syngenetic deposits in shale (not mined at present).	Soil, soil gas, stream and lake sediments, surface or groundwater	Uranium	²²² Rn, He, γ-radiation	Minimum of ~ 2 ft. to maximum depth possible (depends on overburden)	X-ray fluorescence, emission spectrometry, fluorimetry, γ-ray spectrometry, radon analysis
Volcanogenic Cu, Pb, Zn, Ag	Associated with rocks of volcanic arcs of eugeosynclinal systems. Ore most frequently in rhyolites and welded ash-flow tuffs. Typically in massive sulfide lenses.	Soil, soil gas, stream, lake sediment, etc., surface and groundwater, rocks	Cu, Pb, Zn, Ag	SO ₂ , H ₂ S, As, Sb, Hg, Ba	Soil zone of accumulation or deeper if transported overburden	X-ray fluorescence, emission spectrometry, colorimetry, gas chromatography, atomic absorption analysis
Pb, Zn, Cu, Ag in shale or argillites	Syngenetic in black shales formed in basins along a submarine rift zone. Usually associated with volcanics.	Soil, rock, stream and lake sediment, water	Pb, Zn, Cu, Ag	Be, SO ₂ , H ₂ S, As, Sb, Bi, U	Shallow depth only (open pit mines)	X-ray fluorescence, emission spectrometry, colorimetry, atomic absorption analysis, specific ion electrodes
Cu-Mo Porphyry	Large, low-grade (0.5-1.0% Cu) often concentrated by supergene processes. Associated with felsic intrusives, typically at least one member is porphyritic. Mostly sulfide ore—may have large alteration haloes and usually form gossans.	Soil, soil gas, sediments (stream, lake, etc.), water, rocks	Cu, Mo, Au	SO ₂ , H ₂ S, Re, K-rich argillites	Soil zone of accumulation or deeper depending on overburden	X-ray fluorescence, emission spectrometry, colorimetry, atomic absorption analysis, gas chromatography, specific ion electrodes, geophysical methods (e.g. magnetic, induced polarization)

^a Direct Ore Indicator = ore elements and associated minor elements which may be mined as byproducts.

^{a*} Indirect Ore Indicator = pathfinder elements (associated with ore mineralization but not ore elements), secondary gaseous or decay products of the ore, or indicative physical properties e.g. radiation.

TABLE 1B.

Ore Deposit	Occurrence and Geol. Setting	Type of Sample	Direct Ore Indicator ^a	Indirect Ore Indicator ^{a*}	Sampling Depth	Method of Analysis
Mississippi Valley type Pb-Zn deposit	In carbonates, limestone and dolomite, bioherms, usually as sulfides, often follow structural features or old erosional topography.	Soil, soil gas, stream and lake sediment, water	Pb, Zn, Ag	SO ₂ , H ₂ S, Ba, Sb, As, Hg	Zn at shallow depth due to high mobility	X-ray fluorescence, emission spectrometry, colorimetry, gas chromatography, atomic absorption analysis
Low Temp. Au-Ag deposits	Three different types: (1) veinlets in volcanic rock (tuffs) of Au-Ag tellurides; (2) "Carlin" type disseminated in silty dolomite; (3) "Witwatersrand" type in Pre C quartz pebble congl.	Soil, soil gas, stream and lake sediment, water	Au, Ag	As, Bi, Sb, Te, Hg	Soil horizons to weathered bedrock	X-ray fluorescence, emission spectrometry, colorimetry, gas chromatography, atomic absorption analysis
Sn deposits	In veins associated with intrusive rhyolites or as placers.	Stream sediment, soil, (Sn very resistant, obtain only small haloes)	Sn, W, Mo	Bi, Sb, As, F.	Soil to weathered bedrock	X-ray fluorescence, emission spectrometry, colorimetry, specific ion electrode for F
Nickel laterites	Product of extreme weathering of ultramafic rocks, humid climate.	Soil	Ni, Co		Shallow depth, leached soil zone to weathered bedrock	Colorimetry, x-ray fluorescence, emission spectrometry
Bauxite deposits	Product of extreme weathering of Al-rich rock	Soil	Al		Shallow depth, leached soil zone to weathered bedrock	X-ray fluorescence, emission spectrometry
Archean Cu-Ni deposits	Associated with ultramafic rocks of eugeosynclinal belts. Usually massive sulfides, sometimes gossan on surface.	Soil, soil gas, sediments (stream, lakes, etc.), water, rocks	Ni, Cu, Co, Platinoids	SO ₂ , H ₂ S	Weathered bedrock	Colorimetry, x-ray fluorescence, emission spectrometry, atomic absorption analysis, gas chromatography, geophysical methods (e.g. magnetic, induced polarization)

^a Direct Ore Indicator = ore elements and associated minor elements which may be mined as byproducts.

^{a*} Indirect Ore Indicator = Pathfinder elements (associated with ore mineralization but not ore elements); secondary gaseous or decay products of the ore, or indicative physical properties; e.g., radiation.

penetrators can provide a useful prospecting tool for regional and detailed site surveys.

Regional Reconnaissance Surveys

Regional reconnaissance surveys evaluate large areas, ranging from hundreds to tens of thousands of square miles, for evidence of mineralization that may warrant detailed exploration. Sample density may vary anywhere from 4 samples per square mile to 1 sample per 100 square miles (Hawkes and Webb, 1962). Deployment of surface penetrators in a reconnaissance survey would precede any use of ground personnel but should itself be preceded by intensive target selection based on remote sensing data. Remote sensing from satellite (Landsat and Geosat) and from aircraft can select likely targets by identifying pertinent structural and geomorphological features and soil and rock types present (Rich, 1973; Rowan et al., 1976).

Detailed Site Surveys

Detailed exploration surveys require much greater sampling density, and are usually set out on a grid system averaging 100 feet. The final stages of a detailed survey include drilling, trenching or underground excavation (Andrews-Jones, 1968). Extensive use of penetrators would surely be cost prohibitive at this stage of exploration. However, selected data points in particularly inaccessible areas, in permafrost or below glacial ice may be more economically obtained with penetrators than by drilling.

Hypothetical Applications

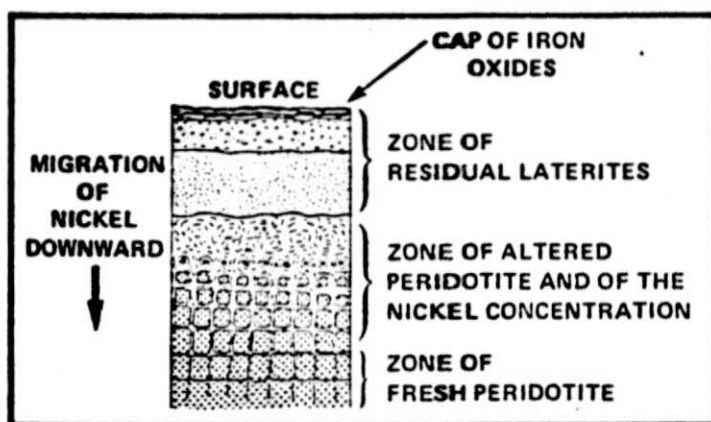
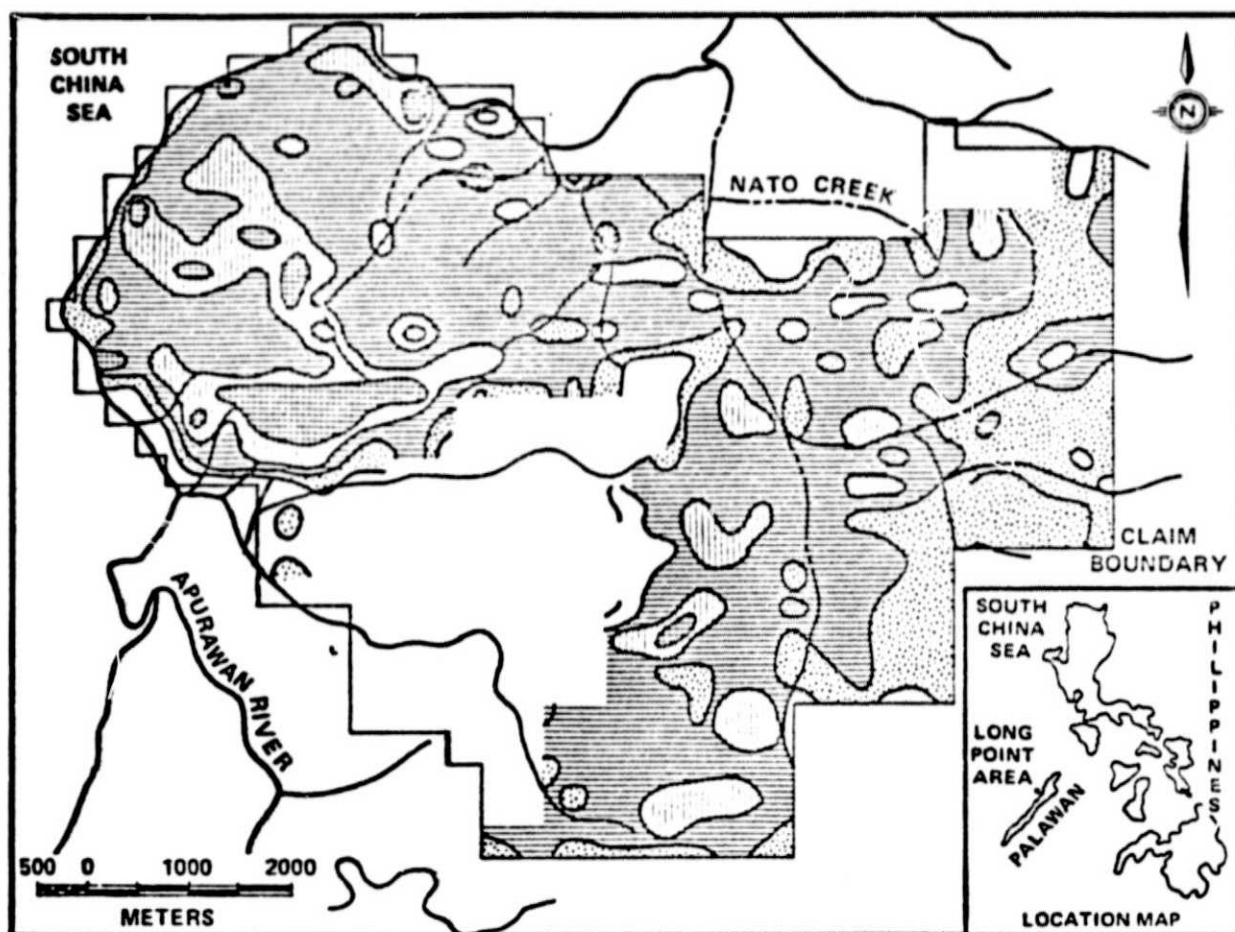
To better evaluate the role of penetrators in mineral exploration, the data and results of three successful exploration surveys for nickel laterite, copper-molybdenum porphyry and uranium ore were used to extrapolate to hypothetical penetrator applications.

Nickel laterite deposits

Geochemical prospecting techniques were successfully used in exploring for three nickel laterite deposits on Palawan in the Philippines (Ong and Sevillano, 1973).

Nickeliferous laterite is the reddish to yellow-brown ferruginous soil, which is the end product of the chemical weathering of ultramafic rock (peridotite, dunite). A generalized section through a typical nickel laterite is shown in Figure 4. A possible nickel ore is a one meter or greater thickness of laterite with an average nickel content of at least 0.9% Ni. The best nickel ores are usually concentrated below the laterite near the top of the weathered, ultramafic rock. The zone of nickel concentration typically lies about six meters below the surface, but occasionally it may lie beneath a cover 20 to 30 meters thick. The best ore development is generally on gentle slopes and on saddles and spurs off flat ridges.

The initial site selection for exploration on Palawan was done from airphotos and topographic maps by locating subdued topography and distinctive vegetation patterns. Then, a reconnaissance survey made traverses across possible laterite areas and collected subsurface soil samples.



EXPLANATION

-  > 15,000 ppm Ni
-  10,000 – 15,000 ppm Ni
-  5,000 – 10,000 ppm Ni
-  1,000 – 5,000 ppm Ni
-  < 1,000 ppm Ni
-  STREAMS

Figure 4. Geochemical map showing nickel concentration in soil in the Long Point area, Palawan, Philippines (modified from Ong and Sevillano, 1975). Insert at lower left shows a typical section through nickeliferous laterite (modified from Park and MacDiarmid, 1964).

The fine fraction (-80 mesh) of the soil was analyzed for Ni and Co by colorimetric methods. All the analytical results were grouped into four geochemical ranges:

- (a) highly anomalous = > 15,000 ppm Ni; > 1,500 ppm Co,
- (b) anomalous = 10,000-15,000 ppm Ni; 1,000-1,500 ppm Co,
- (c) slightly anomalous = 5,000-10,000 ppm Ni; 500-1,000 ppm Co,
- (c) background = 1,000-5,000 ppm Ni; 100-500 ppm Co.

A geochemical map of the Long Point area is shown in Figure 4. Only nickel concentrations are shown since cobalt and nickel produced nearly identical geochemical patterns.

On the basis of the soil analyses, test pits were dug for detailed exploration and ore evaluation. Possible nickel ore was found under highly anomalous soil in 96 to 100% of the test pits, and under 86 to 90% of all anomalous sites. Approximately 70% of the slightly anomalous soil sites also contained possible ore, and even soils with background concentrations had potential ore in a few cases (< 27%).

If a reconnaissance survey employing penetrators had been used in this area, the laterite would have been recognized as a potential ore deposit even with low density sampling (1 penetrator per square mile or less). In fact, the airborne survey and the reconnaissance survey could have been done simultaneously, eliminating the time delay between the planning, sampling and analyzing stages of the survey.

If an inexpensive method for analyzing nickel from penetrators could be developed, it may even be preferable to use penetrators in detailed exploration of laterites to avoid excavation of test pits. Certainly, the time lag that exists between exploration and exploitation of an ore deposit could greatly be decreased by using penetrators.

Copper-molybdenum porphyry deposit

The Casino Cu-Mo porphyry deposit in the Dawson Range, Yukon, Canada, was discovered in 1968 by geochemical prospecting techniques (Archer and Main, 1971).

The deposit is located in the northeast margin of the Klotassin batholith, a medium-grained quartz monzonite to granodiorite pluton of upper Cretaceous age (~ 95-99 m. yrs.). The ore mineralization is associated with the Casino stock, which is one of several quartz-rich stocks that were intruded into the Klotassin batholith in Tertiary times (~ 70 m. yrs. ago). The Casino stock forms an erosion resistant hill, but no true outcrops exist since the area is covered by residual soil and glacial till, ranging in thickness from 3 ft. on hills to 20 ft. on lower slopes. The entire Casino stock and portions of the surrounding batholith have been leached to a depth ranging from 30 ft. at the base of the hill to 350 ft. on the top. Below the leached capping lies a zone of secondary enrichment between 100 and 300 feet thick. A displaced limonite gossan was formed about a quarter of a mile southeast of the deposit where a groundwater spring empties into Taylor Creek (Figure 5).

The presence of a copper porphyry in this area had been suspected for many years. Minerals like chalcopyrite, pyrite and molybdenite had been noted by earlier prospectors who were working gold and tungsten placers in some of the creeks and silver-lead veins in the surrounding batholith. Not until a detailed geochemical survey was conducted, some 70 years later, could the position of the copper porphyry be determined.

The Patton Hill area was soil-sampled on a 400 ft. grid system. The samples were analyzed for Cu, Mo, Au, Ag, W and Pb by atomic absorption and colorimetric methods. Anomalous Cu and Mo values in soil

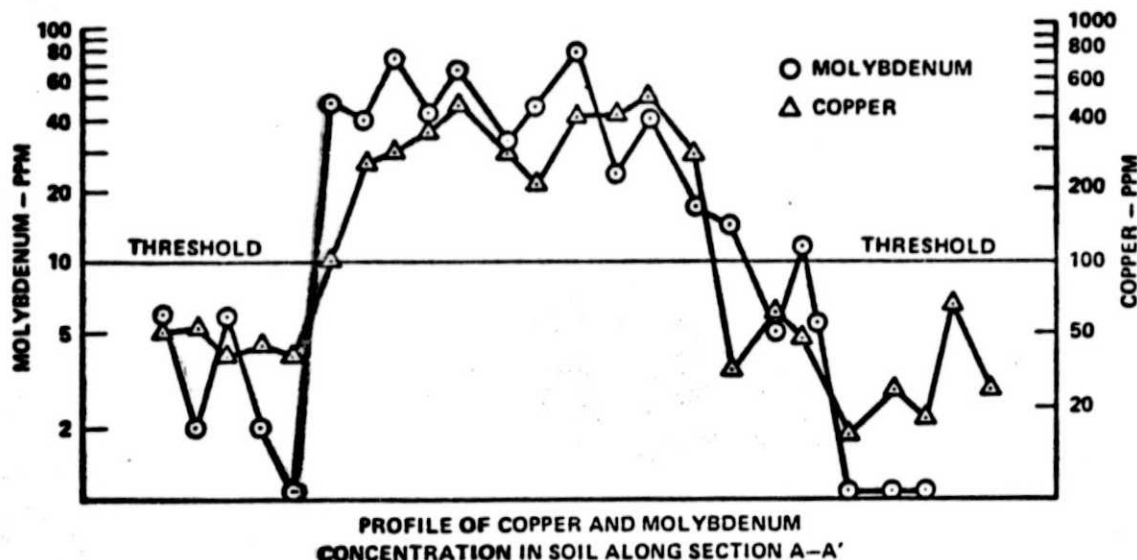
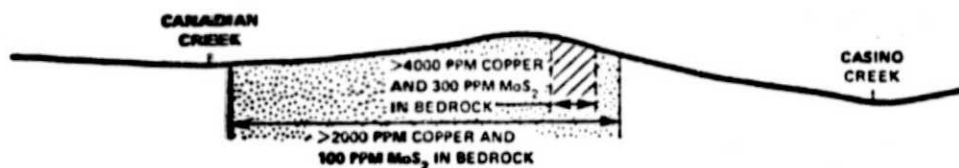
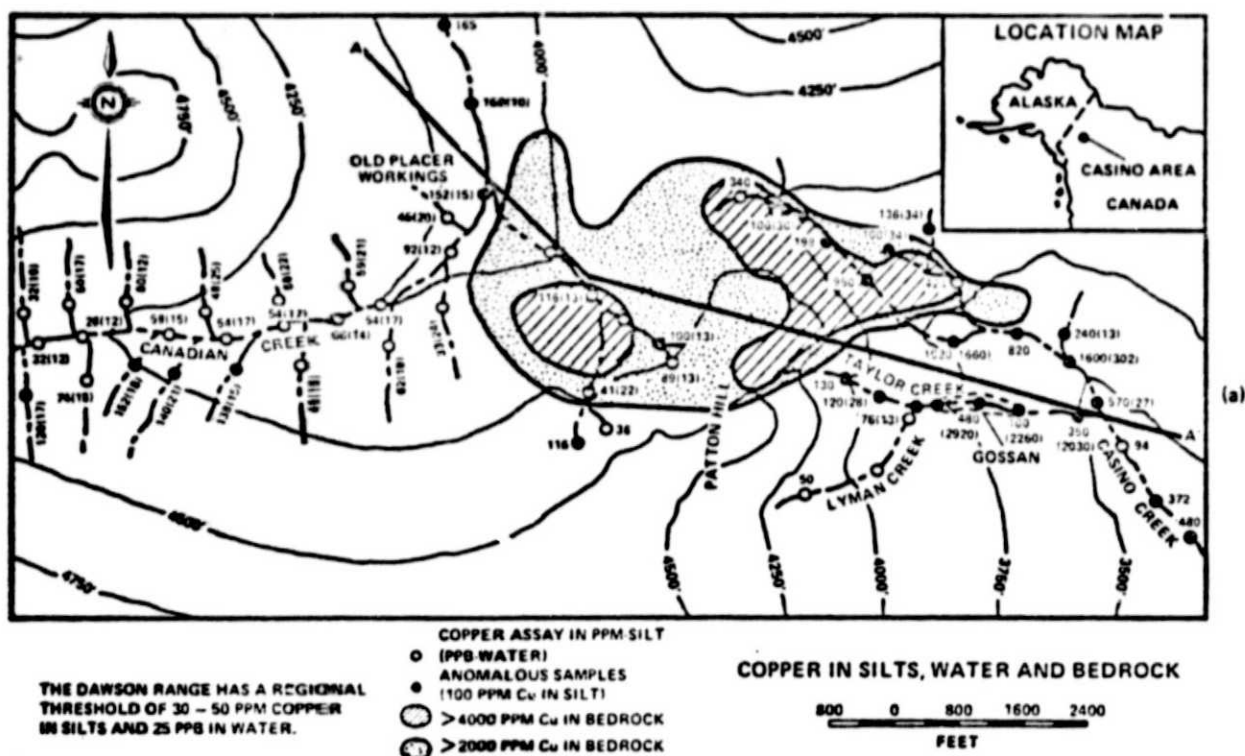


Figure 5. A map of the Casino copper-molybdenum porphyry showing (A) copper concentration in silt, water and bedrock, (B) a cross section along traverse A-A', and (C) copper and molybdenum concentrations in soil along A-A' (modified from Archer and Main, 1971).

and rock clearly identified the mineralized area (See Figure 5).

Au, Ag, Pb and W analyses produced more erratic patterns because of the veins in the surrounding batholith.

Strong Cu-Mo anomalies were selected for drilling and the presence of ore-grade rock below the leached capping was confirmed.

After the ore had been discovered, stream sediments and waters were sampled, not for exploration purposes, but to determine geochemical dispersion patterns. Water samples were generally below threshold values except where groundwater seepage from the ore entered a creek. However, the stream sediments had anomalously high Cu and Mo values that persisted as far as several miles away from the deposit (Figure 5). In fact, Archer and Main suggest that a regional stream sediment survey with a density of only one sample per 10 square miles would have been adequate to locate the area of interest.

Extrapolating from these data to a hypothetical exploration program using penetrators, it appears that a regional survey of stream sediments should have been capable of identifying the general Casino area as a potential ore site warranting more detailed exploration. Using soil or bedrock samples significantly reduces the size of the target area. If, for example, one had chosen a sampling density of one sample per square mile and chosen the bedrock below the gossan as a sampling point, the entire deposit could have been missed. Typically though, gossans are surface indicators of ore deposits and would be logical sampling points in an exploration survey. Displaced gossans are but one example of complications that can be introduced by hydromorphic conditions. Detailed surveys for delineating an ore body of this type require high density (e.g. 400 ft. grid) sampling, a factor which could make penetrators cost prohibitive.

Uranium ore deposits

Exploration studies for uranium ore using radon-in-soil-gas analyses were conducted in selected areas in the Colorado Plateau region (Stevens, et al., 1971).

Analysis of radon was chosen because radon is the only gaseous daughter product of the uranium decay sequence. It has a half-life of 3.8 days, is chemically inert and can migrate under a pressure gradient. Hence, it can greatly enlarge an exploration target and may function as an indicator of uranium ore at great depth.

The method was first tested in the Lisbon Valley area, Utah, over known uranium ores (Figure 6). The soil gas was pumped out of a hole (generally at 4 ft. depth) with a vacuum pump and passed through an alpha particle detector at a fixed rate. Soil chips from the bottom of the holes were analyzed for uranium content to establish that the radon was not a product of uranium adsorbed onto the organic matter in the soil but had migrated to this depth. In each case, the gamma-ray activity on the surface showed no, or only weak anomalies, but the radon in soil gas showed distinctive anomalies over the ores. It was observed that the strength of the anomaly was proportional to the depth to the ore body. The radon concentrations obtained from shallow (6 inch depth) holes were very low because of dilution of soil gas by the atmosphere. Samples from holes 4 ft. deep showed well defined anomalies but were only half as strong as those measured in 10 and 20 ft. holes over the same deposit. However, little difference in concentration was observed between 10 and 20 ft. sample holes.

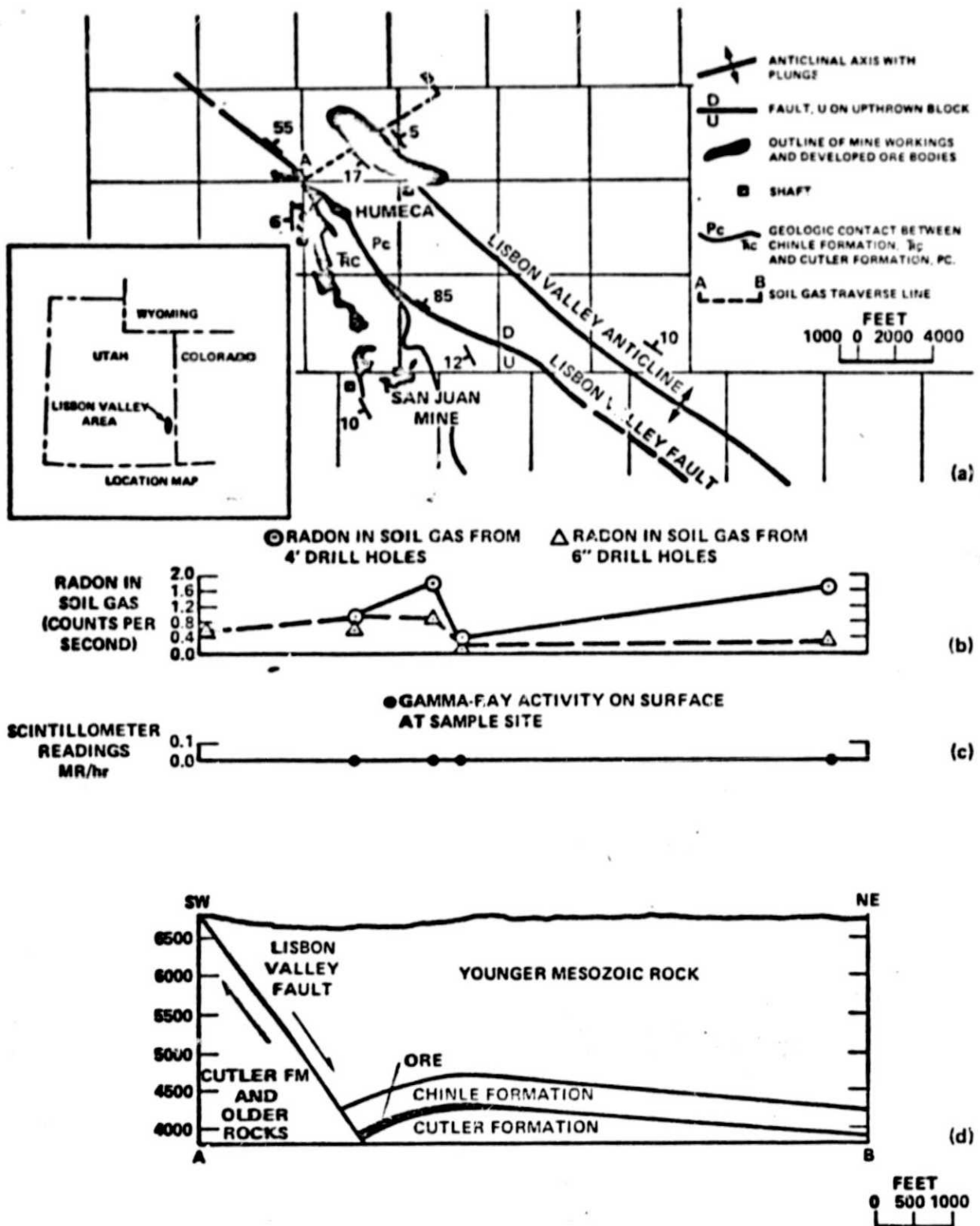


Figure 6. Relationship of radon in soil gas to surface gamma ray activity over uranium ore, showing (A) ore bodies in the Lisbon Valley area, Utah, (B) concentration of radon in soil gas along traverse A-B, (C) gamma ray activity on the surface along traverse A-B, and (D) a geologic cross section along A-B (modified from Stevens et al., 1971).

The method was then applied to similar geologic environments in the Denver and Laramie basins. In the Denver basin the method successfully located a potential uranium ore. In the Laramie basin positive radon anomalies did not lead to an ore deposit apparently because the uranium was concentrated in organic material in the soil.

Extrapolating from these data to a hypothetical survey using penetrators, it appears that penetrators could be useful in exploration for uranium ore. Airborne gamma-ray surveys can only analyze the upper two feet of soil material (due to absorption of gamma-rays). Penetrators capable of soil gas analysis or even equipped only with a Scintillation or Geiger counter, could be employed to confirm weak or confused gamma-ray anomalies detected by remote sensing. Target selection for detailed exploration could be narrowed down by eliminating anomalies that are only surface phenomena. Penetrators could also be used in follow-up surveys, but very careful target selection and interpretation of data, based on geologic evidence, is necessary since many complications in the form of false and displaced anomalies can occur.

INSTRUMENTATION FOR FUTURE PENETRATORS

A wide variety of geochemical and geophysical methods are employed in exploration for natural resources and in environmental geology and engineering applications. To make penetrators effective in many of these applications adaptive modifications will be required to existing instruments. Some instruments have already been demonstrated feasible by previous planetary missions, or preliminary penetrator mission development studies. There are other instruments that have not yet been demonstrated feasible but whose design requirements do not appear to represent difficult tasks. Finally, there is a third group of instruments for which major technologic innovations would have to occur before they could be considered feasible. Table 6 lists potential penetrator instrumentation of these three categories.

INSTRUMENTATION THAT HAS BEEN DEMONSTRATED FEASIBLE

Instruments in this category include a seismometer with tiltmeter, a magnetometer, a decelerometer, an imager and a soil moisture measuring device (Blanchard et al., 1976). In addition to these instruments demonstrated feasible by planetary mission studies, a method for measuring shear strength of undrained sediments has been developed by the U.S. Navy (Beard, 1977), and a method for measuring soil bearing strength has been developed by the U.S. Air Force (Marien and Hansen, 1974).

Seismometer and Tiltmeter

The seismometer and tiltmeter is a single assembly, consisting of a biaxial bubble tiltmeter and a force balance accelerometer which measures horizontal and vertical ground motion, respectively.

Magnetometer

The magnetometer is of the triaxial fluxgate type consisting of two parts, the sensor and the electronic assembly.

TABLE 6.

POTENTIAL PENETRATOR INSTRUMENTATION

Instrumentation which has been demonstrated to be feasible	Instrumentation which appears feasible but not yet demonstrated	Instrumentation that will require major technological innovation to become feasible
Seismometer	Gamma-ray Spectrometer	Emission Spectrometer
Tiltmeter	Alpha-backscatter analyzer	Mass Spectrometer
Magnetometer	X-ray Fluorescence analyzer	Chromatograph
Decelerometer	Specific Ion Electrodes	Atomic Absorption Analyzer
Imager (CCD)	Fluorimeter	Neutron Activation Analyzer
Soil moisture measuring device	Radon Detector (Alpha-particle counter)	Infrared Absorption Analyzer
Undrained shear strength measuring device	Colorimeter	Bacteria Analyzer
Soil bearing strength measuring device	Electrical Prospecting Devices	
	Gravity Meter	
	Thermocouple/Thermistor Arrays	
	Strain Gages	
	Shear Strength Measuring Device	
	Bulk Density Measuring Device	
	Pore Pressure Measuring Device	
	Porosity Measuring Device	
	Permeability Measuring Device	

Decelerometer

The decelerometer, consisting of a piezoelectric transducer, measures the deceleration of the penetrator while it is moving through the soil. Discontinuous changes in deceleration occur when the penetrator moves through different types of earth materials thereby characterizing soil types and gross stratigraphy.

Imager(CCD)

The imager is a CCD type camera using an optically filtered array of silicon photosensors. It is located either in the after or forebody to provide information on surface geology or in situ subsurface microscopy that may be vital for interpretation of subsurface data.

Soil Moisture Measuring Device

The soil moisture measuring device consists of an electrolytic cell containing P_2O_5 and a heating chamber. Measurements of free and bound water from subsurface sediments can be made that may provide information on water in soil, hydrated minerals and presence of permafrost.

Undrained Shear Strength Measuring Device

The undrained shear strength measuring device utilizes the Doppler effect of a moving sound source in relation to the sound receiver. The receiver is aboard a ship while the transmitter is placed in the descending penetrator. The velocity of the penetrator is measured as it penetrates sea floor sediments. From the change of velocity with time, penetrability and an undrained shear strength profile can be estimated.

Soil Bearing Strength Measuring Device

The soil bearing strength measuring device is a very small penetrator consisting of a steel rod and a plastic casing. At impact, the heavier rod penetrates deeper than the casing. As the rod separates, it cuts a series

of wires connected to resistors. From the resultant increase in voltage, soil bearing strength can be determined.

For all of the above instruments future studies need to concentrate on increasing reliability and decreasing complexity and cost.

INSTRUMENTATION THAT APPEARS FEASIBLE BUT HAS NOT YET BEEN DEMONSTRATED

Instruments in this category include a variety of geochemical and geophysical sensors whose design requirements do not appear to present major difficulties. The geochemical instruments include a gamma-ray spectrometer, an alpha-backscatter and X-ray fluorescence analyzer, specific ion electrodes, a fluorimeter, radon detector and some type of analyzer using colorimetric techniques. The geophysical instruments include electrical prospecting devices, a gravity meter, thermocouple/thermistor arrays, strain gages, and a number of devices able to measure shear strength, bulk density, pore pressure, and porosity and permeability of earth materials. Of these instruments only the gamma-ray spectrometer, alpha-backscatter, X-ray fluorescence analyzer and the thermocouple/thermistor array have been addressed by preliminary planetary mission development studies. However, innovations in both geochemical and geophysical sensors of this category are vital if penetrators are to be used in exploration for natural resources and in environmental and engineering geology applications.

Gamma Ray Spectrometer

The gamma-ray spectrometer measures gamma radiation emitted by naturally radioactive elements, primarily U, Th and K^{40} . Gross gamma-ray counters, using a geiger or scintillation counter, measure the total gamma radiation of all radioactive elements present. Gamma-ray spectrometers are able to resolve the characteristic energies of specific

isotopes. The gamma-ray spectrometer consists of a detector and a pulse height analyzer. The detector is typically a NaI or CsI crystal that converts gamma radiation to a flash of light, which is converted to voltage by a photomultiplier tube. The pulse height analyzer separates the voltage into the gamma ray spectrum. Solid state detectors of Li-drifted germanium crystals have higher resolving power than NaI but require cryogenic cooling. Gross gamma-ray counters and gamma-ray spectrometers appear easily adaptable for penetrators. Size limitations present no problem and preliminary shock testing of a CsI crystal and a photomultiplier tube has been successfully performed with deceleration loads up to 2000 g's (Metzger and Parker, 1976).

Alpha-backscatter and X-ray Fluorescence Analyzer

The alpha-backscatter and x-ray fluorescence analyzer investigated by planetary mission development studies is combined in one instrument. It uses a collimated beam of monoenergetic alpha particles from a Cm^{242} source which is backscattered from the sample target and detected by semiconductor detectors. Analytical data of eight elements (C to Fe) is obtained from the backscattering and alpha/proton reactions. Analytical data of heavier elements ($> \text{Si}$) is obtained from X-ray fluorescence induced in the sample by the alpha radiation. Miniaturization of the instrument appears to present no problems; the sensor developed is 4.5 x 4.5 x 4.0 cm in size. However, the germanium semiconductor detector presents a problem because it requires cryogenic cooling. Rapid advances in detectors made of CdTe, that require no cooling, may substitute for germanium detectors (Economou and Turkevich, 1976). The major obstacle to using this instrument in earth applications

is probably that an alpha source is not just expensive but also an environmental hazard. Another power source to induce X-ray fluorescence would be desirable, or at least an isotope source with a very short half-life.

Specific Ion Electrodes

Specific ion electrodes have been developed that are sensitive to certain ions in solutions. The instrument consists of an ion-sensitive electrode, a reference electrode and a specific ion meter. The potential, in millivolts, developed between the sensing and reference electrode depends on the concentration of the ion. The sample solution is compared to standard solutions. Specific ion electrodes are widely used for analysis of fluorine in water and other halogens (e.g., Cl, Br). Electrodes for sulfide and a few metals (e.g., Na, Ca, Ag, Cu) exist but interference by polyvalent ions and complexes may require buffering. Specific ion electrodes are rugged and can easily be miniaturized for use in penetrators. Unfortunately, there are no specific electrodes for many ions of interest in mineral exploration. Also the sample has to be in solution and must be compared to standards for a quantitative analysis (Sherrington, 1970).

Fluorimeter

The fluorimeter is based on the phenomenon that some substances when irradiated by a certain wavelength of electromagnetic radiation will re-emit the absorbed light at a longer wavelength. For example, if a uranium bearing sample is irradiated with ultraviolet light it will fluoresce light in the visible range. This emission can be recorded by a photoelectric cell and quantitative determinations can be made by comparison with standards. Fluorimetry can also be applied to the analysis

of hydrocarbons by using a mercury (Hg) lamp in place of an ultra-violet light source (Levinson, 1974). Fluorimeters appear adaptable to penetrators if the UV or Hg lamp can survive the required deceleration loads. Quantitative analysis requires fluxing of solid samples and comparison with standards, but a semiquantitative estimate may be adequate for reconnaissance exploration of natural resources.

Radon Detector (Alpha-particle Counter)

The radon detector measures the alpha decay of radon, the only gaseous daughter nuclide of the uranium series. Since radon is a gas it can diffuse through rocks and soil from a uranium ore body at considerable depth. Unlike gamma rays, alpha particles cannot penetrate soil and it is therefore necessary to draw or flush out the soil gas. The soil gas is drawn into a ZnS-coated chamber from which all light is excluded. When an alpha-particle is released by the decaying radon it causes the ZnS to fluoresce, and the fluorescence is detected by a photoelectric cell (Levinson, 1974). An alpha-particle counter appears easily adaptable to penetrators, but a pumping mechanism for collecting soil gas samples appears more difficult.

Colorimeter

Colorimetric methods of analysis are essentially wet chemical analyses in which the color intensity of a sample solution, colored by a chemical reaction, is compared to the color intensity of standard solutions. This comparison can either be made visually or with a spectrophotometer. Dissolution of the sample may be done by cold extraction with a dilute acid, or by hot acid extraction, or it may even be necessary to fuse the sample with a flux before dissolving it in acid. Typically several elements can react with one reagent but

a specific pH may be required to allow only the desired element to react. Alternatively, reagents may be added to form complexes with other ions that could interfere with the desired reaction. One of the most widely used reagents in geochemical exploration for mineral resources is dithiozone (diphenylthiocarbazone). Dithiozone, after dissolution in an organic solvent, can react with heavy metals (e.g. Fe, Mn, Co, Ni, Cu, Zn, Pb, Bi, Ag, Cd, Sn and others) to form brightly colored products (Levinson, 1974).

It may be possible to develop a simplified colorimetric analyzer for penetrators using only one reagent (e.g. dithiozone) for a cold extractable total heavy metal test, or by testing for several metal ions by adjusting the pH of the solution. The color intensity could be measured by a spectrophotometer which makes use of the principle that a colored solution absorbs radiant energy of a complimentary wavelength.

To design a system capable of colorimetric analysis that would be able to withstand deceleration loads appears difficult, but worth the effort because it could provide an inexpensive method of analysis.

Electrical Prospecting Devices

Many electrical prospecting methods exist. Some are used in searching for metals. Others are used to obtain information on basement surfaces underlying sedimentary basins. Still others, especially resistivity methods, are used in engineering geology for finding the depth to bedrock and in exploration for geothermal resources. Some of these methods measure naturally occurring currents and fields while others require that electric currents are introduced artificially.

Electrical prospecting methods involve three fundamental properties of rocks: (1) the resistivity (or its inverse-conductivity) which governs the amount of current that passes through a rock; (2) the electrochemical activity which depends on the electrolytes in the ground; and (3) the dielectric constant which is an indicator of the capacity of a rock material to store electric charge.

Resistivity, telluric and magneto-telluric methods, for example, measure the resistivity of earth materials. All telluric methods measure currents and fields that occur naturally in the earth, while resistivity methods require artificial introduction of electric currents. Self-potential and induced polarization methods utilize electrochemical reactions between minerals and surrounding solutions. Self-potential methods measure naturally existing currents while induced polarization methods require externally applied currents (Dobrin, 1976). Many different sensors are available that use some variation of these basic methods enumerated. Typically, a large number of data points are required since gradients, rather than absolute values are determined. For this reason, use of any of these sensors in penetrators would probably be best in the form of a network of electrically connected penetrators. Alternatively, an array of sensors could be placed along the umbilical connecting the fore and after body. Physical adaptation to penetrators does not appear conceptually to present any difficulties for these sensors.

Gravity Meter

The gravimetric method measures the variation in the earth's gravitational attraction from one point to another. The variations in gravity observed in a given area depend mostly on changes in

density of rocks in the vicinity of the measuring point. The gravimetric method has been used to map sedimentary basins where the basement rocks have a higher density than the sediments. It has also been used to detect low density salt bodies and heavy mineral concentrations such as chromites. Gravity measurements have been made with the torsion balance, the pendulum and the gravity meter. The first two are obsolete. The gravity meters in use today measure the displacement of a responsive element (such as a spring) due to the change in gravity. Displacements are always extremely small and must be greatly magnified by optical, mechanical or electrical means (Dobrin, 1976).

Gravity meters are conceptually simple and easily miniaturized. However, the great sensitivity and delicate alignment necessary to make meaningful measurements would make them extremely sensitive to deceleration loads.

Thermocouple/Thermistor Arrays

Thermocouple/thermistor arrays can make heat flow measurements and determine thermal gradients that are of primary interest to geothermal exploration. Thermocouples consist of two dissimilar metal conductors joined together in two places. If the measuring and reference junctions are at different temperatures an electrical potential proportional to the temperature difference will exist in the circuit. Thermistors measure the temperature-dependent change in resistivity of a semiconductor. These sensors respond rapidly to very small temperature changes. They are small and appear easily adaptable to penetrators. An array of thermocouples and thermistors could be deployed either along the umbilical cord connecting the fore and afterbody, or as a series of radial probes projected out of the penetrator forebody.

Strain Gages

Strain gages are electrical, mechanical or optical devices for measuring the changes in the distance between points in solid bodies as the bodies are deformed. Two of the most commonly used devices are the electric resistance and the vibrating wire strain gages. The electric resistance gage consists of a wire grid pattern bonded to the surface on which the strain is to be measured. When the surface is deformed the wire stretches or contracts and a change in resistance results that is proportional to the strain. The vibrating wire gage consists of a thin steel wire held against the unit under strain. Electrical currents induce the wire to vibrate at a given frequency. Changes in strain affect the tension of the wire and hence the frequency of the vibrations.

Either one of these methods could be employed by penetrators. A grid could be part of the penetrator's forebody while a wire gage may be placed in the umbilical cord connecting the fore and afterbody. Other possibilities exist for deployment of penetrators in a strain-monitoring network along active fault zones. For example, the distance between fore and afterbody could provide a measure of strain of the rock unit in which the penetrator is embedded.

Shear Strength Measuring Device

Shear strength measuring devices measure the internal resistance of materials to shear stress. Shear strength is an important property of soils, providing supporting ability of bearing strength for structures. Several popular methods to measure shear strength of soils exist. For example, unconfined compression tests applying axial compression as principal stress, triaxial tests applying lateral and compressional

stresses, vane shear and direct shear tests are used in laboratory shear strength experiments. Vane shear tests use a four-bladed vane on the end of a drill that applies torque to the soil sample between the vane blades until it is sheared. Direct shear tests use a soil box consisting of two horizontally movable segments. After applying a vertical load the segments are pulled apart horizontally until the soil is sheared.

The last two shear strength measuring devices may be adaptable for penetrators.

Bulk Density Measuring Device

Bulk density measurements are commonly performed by actually weighing the excavated material or by filling an excavated hole with calibrated material. Another method relies on the principle that transmission or scattering of gamma-rays is dependent on the density of the surrounding materials. In the gamma-ray transmission technique, probes are used at a fixed distance. One contains the gamma-ray source; the other the detector. In the scattering technique only one probe is used containing both the source and a shielded detector to measure the back-scattered radiation.

Either gamma-ray technique could be easily adapted to penetrators but a radioactive isotope source would constitute an environmental hazard in a discardable penetrator. A possible alternative method of at least estimating bulk densities may be obtained from the deceleration record. Experimental data from units with known densities would have to be acquired for calibration.

Pore Pressure Measuring Device

Pore water pressure measurements are typically made with either a hydraulic or electric piezometer. Only the electric piezometer could be used in penetrators. The electric piezometer requires no

appreciable flow of water to register a change in pressure. A calibrated membrane is deflected by changes in pore pressure and the amount of deflection is measured electrically. Electric piezometers appear readily adaptable to penetrators.

Porosity and Permeability Measuring Devices

Porosity and permeability measurements of earth materials are important in engineering geology, especially in evaluation of dam sites. Porosity is the ratio of volume of voids to the total volume of soil or rock. It can be measured in the field by using the air-space pycnometer method. The soil sample is placed into one of two connected, air-tight chambers. The other chamber serves as an air reservoir that supplies air into the sample chamber through a connecting valve. The reservoir pressure can be related to volume of air space in the sample cylinder. To convert pressure to percent air space a calibration curve has to be established using standards.

Permeability is the property of a soil or rock which permits water to flow through its pores, and hence is dependent on porosity. Permeability measuring devices used in the laboratory are of two types. One, the constant head type measures the discharge of water at the base of the soil or rock column. The other, the varying head type measures the quantity of water entering a soil by monitoring the water level in a calibrated pipe.

None of these methods appear ideally adaptable to penetrators even though they are feasible. It would be preferable if some simpler method such as a piezometer could be used for indirect measurements from which porosity and permeability could be calculated.

INSTRUMENTATION THAT WILL REQUIRE MAJOR TECHNOLOGIC INNOVATIONS TO BECOME FEASIBLE

Instruments in this category include emission and mass spectrometers, chromatograph, atomic absorption analyzer, neutron activation analyzer, infrared absorption analyzer, and bacteria analyzers. Some of these, especially the emission spectrometer and the atomic absorption analyzer, represent the most commonly used analytical methods in current mineral exploration programs, and gas chromatographs and mass spectrometers are frequently used in fossil fuel exploration. The reason that these are popular is based primarily on their ability to detect low concentrations of key elements or compounds in the geologic environment. While bacteria analyzers are currently of primary interest to extraterrestrial exploration; they may also be useful in earth applications by detecting hydrocarbon oxidizing bacteria indicative of petroleum deposits. The modifications necessary to reduce these instruments to small size to fit in penetrators and to enable them to survive the shock at impact provides a major challenge.

Emission Spectrometer

The emission spectrometer is based on the phenomenon that atoms raised to an excited state by means of arcs, sparks or lasers emit light of a spectrum that is characteristic for each element. The intensity of the emitted radiation at the proper wavelength is proportional to the concentration of that element in the sample. Emission spectrometers consist of three main components: (1) an excitation source to volatilize the sample; (2) a dispersing device to separate the light into its component wavelengths and (3) a recording device to measure the intensity of individual wavelengths. The type of spectrometer that records intensity electronically is known as a direct reading

emission spectrometer. Its main advantage is the ability to analyze 15 to 40 elements simultaneously (Wainerdi and Uken, 1971). The greatest difficulty in adapting emission spectrometers to penetrators would probably be in providing a power source capable of volatilizing soil and rock samples.

Mass Spectrometer

The mass spectrometer is based on the principle that when a substance, at low pressure (10^{-6} torr), is bombarded with low energy electrons a beam of positive ions can be withdrawn from the impact area. The ions in the beam are sorted by magnetic fields according to their masses. Many different models of mass spectrometers exist but all have three essential components in addition to a vacuum system: (1) an ion source, consisting of a heated filament or spark source (50-100 kv) to convert neutral molecules into ions; (2) an analyzer consisting of a combination of magnetic and electric fields to split the ion beam into the mass spectrum according to the mass/charge (m/e) ratio; and (3) an ion detector system to measure and record the mass spectrum. As many as 70 elements can be analyzed simultaneously by this method, with sensitivities far superior to emission spectroscopy (0.01 ppm range versus 10 to 100 ppm range) (Wainerdi and Uken, 1971). The need for a high energy source, a vacuum system, the general bulkiness, and the inability to withstand shock loading present adaptation problems that may be insurmountable.

Chromatograph

Chromatographic methods of analysis separate the individual components of a mixture by taking advantage of differences in adsorption of various materials. The mixture to be analyzed can be separated by

differential adsorption onto a substratum of either paper or film (paper and thin-layer chromatography) or a powder packed into a column (column chromatography). Alternatively, separation can also be achieved by a partition process (i.e., retardation of a solvent on a liquid-coated inert solid), or a combination of adsorption and partition, or by an ion exchange process. In gas chromatography a vapor sample is introduced into a moving stream of a carrier gas (usually helium) and the components are separated by a stationary phase in a column. The stationary phase is either an adsorbing solid (gas-solid chromatography) or a liquid held as a thin film on an inert solid (gas-liquid chromatography). The separated components emerge individually at the end of the column where they can be detected and measured by a variety of detectors using either thermal conductivity or density of the gas, or some spectroscopic method. This method of analysis is very sensitive, measuring concentrations in the ppb range (Wainerdi and Uken, 1971).

The greatest problem in adapting the gas chromatograph to penetrators would be shock hardening the column.

Atomic Absorption (A.A.) Analyzer

The atomic absorption analyzer is based on the principle that unexcited atoms can absorb the energy of a beam of light of the same characteristic wavelength. In a typical atomic absorption analysis the dissolved sample is aspirated into a flame, fueled by a mixture of air and acetylene, which reduces the droplets into a vapor of neutral atoms. The vapor is illuminated by a light source (hollow cathode lamp) radiating the characteristic light of the analytical element. The atoms of that element in the vapor will absorb the incident radiation from the cathode lamp. The radiation, now reduced in intensity

because of absorption, is isolated by a monochromator and measured by a detector. The amount of absorption is proportional to the concentration of the element in the sample. With a typical A.A. analyzer the sample is analyzed for one element at the time, but recent developments are attempting to provide multi-elemental analysis by using resonance detectors around a common atomizing flame. Some volatile elements like Hg, As, etc. may be driven off by heating the sample and then analyzing the vapor by flameless atomic absorption. Another modification of an A.A. analyzer has been developed in the carbon rod furnace which can analyze a solid sample directly (Wainerdi and Uken, 1971). None of the existing A.A. analyzers appears readily adaptable for penetrator use. They are bulky in size, requiring a gas supply and/or a relatively high energy source, but, perhaps most significantly, they require geometric alignment of monochromator entrance and exit slits that would be sensitive to high deceleration loads.

Neutron Activation (N.A.) Analyzer

The neutron activation analyzer is based on the principle that when a material is bombarded with a stream of neutrons some of the atoms of each element present are converted into a radioactive species. These radioactive species emit characteristic radiation that can be identified and measured by a multichannel analyzer. The NAA method is very sensitive and concentrations in the 0.1 ppb range can be detected. Typically, NA analyzers are large complex systems where samples are irradiated in nuclear reactors or particle accelerators. However, for trace element analysis, a radioactive isotope can also function as a radiation source (Wainerdi and Uken, 1971). Although

NA analyzers with an isotope source would be very useful in extraterrestrial exploration, they would be an environmental hazard when used in discardable penetrators.

Infrared Absorption (IR) Analyzer

The infrared absorption analyzer is based on the principle that infrared radiation can activate chemical bonds. In contrast to and visible radiation which have enough energy to cause transition of energy levels of electrons in the outer shells of atoms, the lower energy of infrared radiation induces vibration in interatomic bonds. The composite pattern of vibrational frequencies at certain wavelengths is uniquely characteristic for a given compound. Infrared spectra of minerals are very complex and may be difficult to interpret. Spectra of hydrocarbons, especially of gases, are simpler and easier to identify. Typically, IR analyzers consist of three major components: (1) a source of infrared radiation; (2) an infrared energy disperser in the form of a prism or grating; and (3) a system for detection of IR radiation, amplification and recording of signal (Lyon, 1967).

The greatest obstacle in modifying an I.R. analyzer for penetrators would be in shock proofing the I.R. radiation source and the dispersion system.

Bacteria Analyzer

The concept of using bacteria to locate gas and oil accumulations is not new (Kartsev et al., 1959) but no instrument has been developed for this purpose. There are numerous possibilities for bacteria analyzers. They may measure the growth of bacteria, the uptake of nutrients and oxygen, or the production of CO₂ from respiration. All methods would use

a measured quantity of sample dispersed in a medium favorable for growth of hydrocarbon oxidizing bacteria. The growth medium may be radioactively labeled to allow rapid detection of low concentrations. Bacteria growth can be detected (1) by measuring the decrease in intensity of a light beam through a bacterial suspension, or (2) by detecting radioactively labeled nutrient incorporated into cellular material. Other parameters which could be measured include the uptake of nutrient or oxygen, and the production of CO_2 from respiration. The instrumentation required to detect bacteria growth by measuring the decrease of light intensity through a bacterial solution, or the decrease in nutrients, appears relatively simple for incorporation into penetrators. The major problem would be acquiring an unaltered sample.

The problem of sample acquisition exists for all of the instruments listed in this category, as well as for some of the instruments listed in group 2. A mechanism to pump air out of the soil and into the penetrator is necessary for gas sample analysis, and a crushing, grinding, and dissolution process is necessary for most solid samples when using geochemical methods of analysis.

CONCLUSIONS

Penetrators have potentially important uses in many earth applications. They have already been effectively employed for making useful civil engineering measurements in remote regions. Measurements of soil strength have been obtained to evaluate potential landing sites for aircraft, and measurements of undrained shear strength in offshore marine sediments have been performed to evaluate embedment anchor sites. Further, penetrators have been employed for hazard monitoring. In this application they were used to measure thickness of floating sea ice which posed potential hazards to ships in polar regions.

Penetrators also appear to be useful for reconnaissance, and possibly some detailed studies, during exploration of mineral deposits, oil and gas accumulations, and geothermal resources. Comparisons between traditional exploration methods and assumed penetrator methods for mineral deposits have indicated potential applications exist for locating nickel rich laterites, copper-molybdenum porphyries, and areas of uranium mineralization. Similar comparisons for oil and gas accumulations indicate potential applications exist for locating offshore (and perhaps onshore) deposits by finding anomalously high concentrations of hydrocarbons. Similar comparisons for geothermal resources indicate potential applications exist for locating favorable sites having both high thermal gradients and microseismic activity.

The success of the penetrator for any of the above applications is dependent upon the availability of appropriate sensors to make the desired geophysical, geochemical or biological measurements. Fortunately, some rather complex sensors have already been demonstrated feasible as a con-

sequence of development studies for planetary applications. There are many other sensors that appear easily modified to meet the high g loads experienced by the penetrator. There also are many other sensors that are extremely important to exploration because they measure gaseous, liquid and solid materials at very low levels (e.g. ppm and ppb range) but currently appear beyond the state of the art in adaptability for the high g environment. Clearly, major technological innovations will be necessary during the coming decades before these sophisticated instruments could be used.

For the penetrator concept to be considered a useful exploration tool it must either: (a) perform the traditional investigations at a comparable cost, or (b) provide needed information more quickly and with less complexity for acquisition and data interpretation. Because serious shortages have been forecasted for certain earth resources in the next 10 to 20 years, no one can accurately predict what exploration costs will be in the future. Therefore, any study attempting to make meaningful comparisons between current exploration costs and likely penetrator costs will be very difficult, if not impossible at this time.

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